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VESTIBULAR AND OCULOMOTOR FUNCTION DURING Gz VARIATIONS

by

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SUMMARY

10 normal subjects were exposed to G-force variations during parabolic flights and turns in a SAAB Supporter aircraft. A vertical head drift accompanied by a vertical eye drift was recorded in all subjects. The eye drift was most prominent during the hyper-G phase of the parabolic manoeuvres. Compensatory eye movements were induced by horizontal head rotations. No statistical significant changes could be demonstrated in this reflex. Horizontal oculomotor saccades were induced with a visual distance of $\pm 10^\circ$. A significant increase of the latency time could be demonstrated during the weightless phase of the parabolas. It is concluded that spontaneous eye and head drift and disturbances in voluntary eye movements might contribute to the development of motion sickness during combat manoeuvres and space flight.

INTRODUCTION

During aviation, spatial disorientation might appear whenever a linear acceleration of the aircraft interferes with the perception of the gravitational force. Unexpected and contradictory sensory cues might cause motion sickness. During space missions, the frequent appearance of space motion sickness not only affects the crew member's comfort but interferes with their productivity and the safety of the missions. The free fall phase of parabolic flights is an important tool for the study of immediate physiological reactions to weightlessness. Lackner & Graybiel (1) were the first to report on alteration of the gain of compensatory eye movements elicited by passive rotation in yaw during parabolic flights. Later, our group (2) was able to demonstrate similar alterations in the gain of compensatory eye movements elicited by voluntary horizontal head rotations. In both studies, the gain decreased during hypogravity and increased during hypergravity. Bludworth et al. (cited in 3) found that the gain of the vestibulo-ocular reflex decreased both in hypo- and hypergravity. The aim of this study was to observe whether opening of the eyes in darkness affected the gain variations caused by Gz variations. Further, we wished to study a phenomenon reported by von Baumgarten et al. (4). During rollercoaster flight vertical nystagmus was observed. A vertical eye drift might interfere with horizontal eye movements and by that influence the results of studies of horizontal eye movement phenomena. By itself, a vertical eye drift might contribute to sensory conflicts and cause spatial disorientation and motion sickness. Vertical eye drift might be elicited by a head drift in the opposite direction and serve as a compensatory measure to the head drift. Because of that, we decided to do simultaneous recordings of head and eye drift in pitch.

In most studies dealing with eye movements in yaw and pitch, electro-oculography is the method used for eye movement recording. This technique is based on the existence of the corneofundal electrical potential. Variations in the intensity of light changes this potential and makes it mandatory to perform calibrations in immediate relation to the experiments. Calibration is performed by fast saccadic eye movements between light-emitting diodes. A disturbance of this voluntary eye movement reflex might contribute to disorientation during variations in the Gz forces. Our experimental setup made it easy to evaluate this reflex in the same procedure. For these reasons it became a specific part of the present parabolic flight study.

METHODS

Ten subjects with normal vestibular pretest were selected for the experiments. None of them were professional pilots, but all subjects had some experience as passengers in small aircrafts. This qualification was preferred to avoid anxiety reactions during the flights. A SAAB Supporter aircraft was supplied by the Royal Danish Air Force. It is designated T-17, in daily service it is used as a training and reconnaissance aircraft. It is a small, two seated propeller driven aircraft well fit for aerobatic manoeuvres. In each mission three series of consecutive parabolas were interrupted by one minute 60° turns with a constant G-load of two G. Convenient pauses with straight and level flight were interpolated between stressful manoeuvres according to the subjects' wishes.

Horizontal and vertical eye movements were recorded simultaneously by means of superficial skin electrodes. DC-amplification was performed with a time constant of ten seconds. Head movements in yaw and pitch were recorded by an angular velocity sensitive device (Rateometer) mounted in a firm head holder. G-load was recorded by a linear accelerometer. An instrument tape recorder carried by the aircraft recorded the signals. The subjects were adapted to darkness by means of red glasses before and during the flights.

During the first sequence of five parabolas and one minute of two G load, the subjects were instructed to keep their eyes open behind a cover and to keep their heads still. During the next sequence, the subjects performed horizontal head rotations guided by an 0.4 Hz frequency modulated sound signal presented to a set of ear phones from a

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tape recorder. During the third and last sequence, the cover was removed from the eyes and the subjects fixed alternately activated red-light-emitting diodes. The duration of each stimulus was randomized. The visual distance between the two diodes was $\pm 10^\circ$ horizontally. Eye movement calibration was performed by means of the same equipment.

After return to the laboratory, data were analysed off-line from the tape recordings. Vertical eye movements appeared in the form of vertical nystagmus. Fast components were identified by a computer program and removed from the signal. Slow components were connected with each other by extrapolation. Compensatory eye movements were analysed according to our laboratory procedure described elsewhere (5). Results appeared as gains and phaseshifts of the transfer function between head movement input and oculomotor output. Latency times of saccades were measured and the peak velocity of the saccade computed from a digital differentiation of the eye signal. Vertical head position data were computed by a digital integration of the head velocity signal from the y-axis sensor.

The duration of all separate parabolas were almost exactly 10 sec.

RESULTS

Vertical eye and head drift:

Fig. 1 demonstrates the mean eye and head movement data of all ten subjects as an average of all parabolas flown. The eye position data describe the eye drift in the direction of the slow phase of nystagmus, whenever nystagmus was present. This explains the offset between eye position at time zero and eye position at 20 sec. The averaging was triggered by the sudden transition from weightlessness to high G-load, which appeared by pull-out from the parabola.

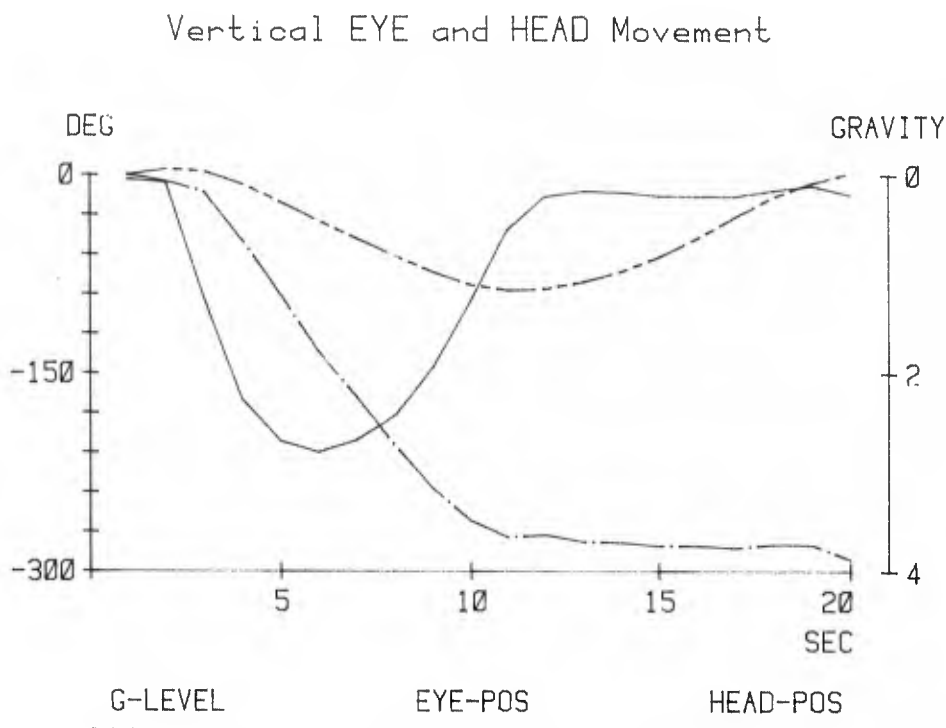


Figure 1. Average eye drift in the direction of the slow nystagmic phase and head position from 10 subjects, 5 parabolas each. Averaging is triggered by the transition from weightlessness to high G-load during pull-out.

All subjects exhibited vertical upward beating (direction of the fast component) nystagmus during high G-load. The nystagmus appeared within the first 1-2 seconds of pull-out from the parabola and disappeared with transition to weightlessness in the next parabola. Careful examination of the original recordings revealed very weak downward beating nystagmus during weightlessness in three of the ten subjects. Slow phase velocity being 2-3 $^\circ$ /sec, the nystagmus was too weak to be recognized as such by our computer analysis.

Head movements were smooth, directed downwards during hypergravity and upwards during hypogravity. This configuration suggests that there is a simple connection between the variations of the weight of the head and the movements. The head reaches its maximal speed in the downward direction 2.5 sec after the maximal G-load.

Compensatory eye movements:

Results of the compensatory eye movement test appear in tab. 1.

It's obvious that there is no difference at all between gains at 0 G and gains at 1 G. The gain at 2 G is lower than the two other gains computed, though no statistical significant difference can be demonstrated, probability level being above 0.05. Intraindividual differences of phaseshifts are high and no statistical significant G-dependence can be extracted from our results. Spectral purity of the responses is lower in this experiment than those obtained under laboratory conditions. This explains the high variability.

	0 G		1 G		2 G	
	GAIN	PHASE	GAIN	PHASE	GAIN	PHASE
\bar{X}	0.83	-21.8°	0.84	-21.4°	0.65	-20.2°
SD	0.20	28.2°	0.23	24.0°	0.25	31.1°
N	10	10	10	10	10	10

Table 1. Gain and phaseshift of compensatory eye movements induced by 0.4 Hz head rotations in yaw at different G-loads. No statistical significant differences can be demonstrated.

Saccadic eye movements:

Results of saccadic eye movement tests appear in tab. 2.

	0 G		1 G		2 G	
	LAT. TIME	PEAK VEL.	LAT. TIME	PEAK VEL.	LAT. TIME	PEAK VEL.
\bar{X}	261 msec	374 °/sec	227 msec	356 °/sec	237 msec	347 °/sec
SD	21.5 msec	27.0 °/sec	22.8 msec	21.6 °/sec	28.6 msec	33.1 °/sec
N	9	9	9	9	9	9

Table 2. Latency time and peak velocities of horizontal randomized saccades with an amplitude of $\pm 10^\circ$ at different G-loads. Italicized figures are statistical significantly different at a probability level below 0.05.

It appeared from tab. 2., that only nine subjects contributed to the results. One of the subject followed his own rythm during flight tests and was omitted from the material. Latency times at 0 G are significantly longer than latency times at higher G. A tendency to higher peak velocities at weightlessness is not statistically significant.

DISCUSSION

Vertical head drift was measured in relation to the earth vertical, we did not do any efforts to subtract the flight profile in order to achieve a measurement of movement in pitch in relation to the aircraft. Flight profile is almost rectilinear, except at maximal and minimal altitude. If the ratemeter recording only described the flight profile, a distinct minimum and maximum would be expected at 5 and 15 sec respectively. The vertical semicircular canals responds to angular accelerations relative to earth vertical. From a recording of rotational rate relative to the aircraft, it would be difficult to predict canalicular vestibular responses. The velocity of the head in pitch is almost exactly in phase with the G-load. This allows us to conclude, that the head movement is a simple consequence of the variations of the weight of the head. The position of the subject in the seat with the head bended a little forward explains the direction of the movements.

Movements of the head in pitch will induce compensatory eye movements in the same axis. However, the eye movements recorded are not compensatory to the head movements and are consequently not caused by the head movements. von Baumgarten et al. (4) conclude, that vertical nystagmus during gravity changes is caused by a central misinterpretation of vestibular information as being caused by involuntary forward or backward tilts. In both cases the utricular receptors would signal a change in the direction of the gravity load. A signal reporting a change of the size of the gravity vector must be substantial different from that. Compensatory eye movements during free fall or during +Gz acceleration should have an upward and downward direction respectively. For that reason, we conclude, that the nystagmus recorded is a relevant central interpretation of a vestibular signal caused by variations of the Gz-load on the utricular receptors. We are unable to explain the non-linearity of the response, the hypergravity response being much stronger than the hypogravity response. In a recent paper, our group has shown that the gain of the compensatory eye movement response to head rotations in yaw varies proportionally to the G-load (2). As discussed below, we were not able to confirm this observation in the present study. Nevertheless, the behavior of the vertical eye drift might be caused by the effects of varying gravity load.

The results of the compensatory eye movement study are difficult to explain in view of the findings from a similar study performed one year before the present study (2). In our first study, subjects performed head rotations with their eyes closed, in the present experiment, eyes were open but covered. All other variables were kept constant. Even the pilot was the same in the two experiments. Four subjects participated in both studies and their results perfectly reflect the different conclusions of the two experiments. Absolute gain values were on average 19% higher in the present study. This difference is statistically significant. In the first study (2) a significant G-dependence of the gain was demonstrated as mentioned above. Gains were 8.5% lower at 0 G and 17% higher at 2 G. The study confirmed the findings of Lackner & Graybiel concerning the oculomotor response to passively induced head rotations. In a recent article Lackner & Graybiel (3) quote Bludworth et al. in a yet unpublished work for having found gain to be decreased during both free fall and at two G force levels. Our experimental design forces us to conclude, that the quantitative and qualitative differences between the results of our two experiments are caused by the difference in the state of vision in the two experiments, closed eyes in the first and open eyes behind covers in the present.

The disturbance in saccadic eye movements demonstrated is statistically significant. It's doubtful whether it can be considered of any significance in aviation or space missions. Somebody might claim that an increased reaction time could be disastrous in high performance fighter combats, but usually negative G-forces are avoided under these circumstances. In the neurological clinical practice, disturbances in saccadic function are interpreted as

a sign of brain stem lesion. Indeed, no such lesion was present in the subjects. Our knowledge of brain stem circulation is rather insufficient. Nevertheless it seems probable that the minor impairment of saccadic function seen in this study could be caused by an impairment of brain stem circulation due to the redistribution of blood volume during weightlessness. Further experiments are needed to shed light on this phenomenon.

It was observed that fixation during saccade tests stabilized eyes in a way that no vertical eye drift could be seen. Head drift disappeared as well.

All together, vertical eye drift, vertical head drift, changes in the gain of compensatory eye movements and disturbances in voluntary saccadic eye movements might cause major disturbances in visual function under flight conditions with shrinking and reexpansion of the gravitational vector. The disappearance of eye drift during visual fixation emphasizes the importance of the state of visual function and no other conclusion concerning oculomotor function during changes in G-vector size can be drawn, than lots of factors might influence function in a way that makes visual fixation ability the crucial factor.

CONCLUSIONS

Following conclusions are drawn from this work:

- I: Hypergravity induces a spontaneous downwards directed eye and head drift.
- II: Hypogravity induces a spontaneous head drift upwards. An eye drift in the same direction is less pronounced and only present in some individuals.
- III: The above mentioned phenomena disappeared with visual fixation.
- IV: Eye opening behind a cover increased the gain of compensatory eye movements and made the response less sensitive to gravitational changes compared to results obtained with eyes closed.
- V: Latency time of saccadic eye movements is prolonged during short periods of weightlessness.

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DISCUSSION

VON GIERKE: In your paper as well as in the previous paper by Professor Lackner I wonder if not the dynamics of the G-time history has to be taken into account. It appears as if in the parabolic zero G flights the oscillations i.e. the period between zero G and maximum G loading is in the order of 10 to 100 seconds. That is, according to steady state laboratory experiments, the frequency range of maximum vestibular response and motion sickness sensitivity. A statement of increased amplification at 2G should probably be qualified as occurring at 2G peak values at the particular oscillation frequency. Do you agree that the dynamics of the G exposure must be stated, analyzed and taken into account? That the frequency might be just as important as the G amplitude?

VESTERHAUGE: Yes, I agree with you. It should be stated that the experiments were performed at a relatively high G-load frequency (about 0.05Hz) compared to other experiments with longer duration of weightlessness.

VON BAUMGARTEN: I find it very important to look at the first push over and the first pull-out because if you do roller-coaster flight you come into a pattern of your subjects anticipating the next move of the aircraft; especially in the small aircraft, the parabolas are 5 or 10 sec. I see from your diagrams that you did the same thing. You said that head movements were caused by simple mechanical forces on the head. That's a possibility. We have not seen these vertical head movements for the reason that we worked with restrained heads in our studies. I would have explained them as a vestibular reflex. We know there is head nystagmus of some patients in the same direction as the eyes flick and if you put someone on the Barany chair and accelerate him he moves his chin against the direction of rotation; and if you rotate him about the Y axis, I would also expect a head movement.

VESTERHAUGE: I'm happy you say that because we believe it might be a vestibular reflex as well. But it's very difficult to prove that it's not just a consequence of the weight of the head changing with acceleration variations.

VON GIERKE: I have no question, just a comment to the last discussion. In 2G, you know that the spinal column is compressed, you must expect head motion between 0G and 2G of more than an inch. That's just spinal dynamics.

RESCHKE: We have also done some very similar things during parabolic flight. Did you notice a lot of variation in the individual subjects in terms of the gain and phase in the eye movements both in vertical and horizontal? For example, were there different patterns? Overall, generally what we found with the horizontal canal stimulation was that during 2G and 0G there was a decrease in the gain and phase. However, with the vertical canals we found an increased gain in 2G and a decreased gain in 0G relative to 1G but this was a general pattern. None of it was statistically significant and every subject seemed to have their own type of pattern although you could begin to group them. I was wondering if you perhaps find the same thing?

VESTERHAUGE: I would agree with you that there is quite a lot of variation in the data especially in the last experiment where I reported about compensatory eye movement. We had quite a lot of variation but the variation was much less with eyes closed than with eyes covered. We had the same experience in the laboratory that these experiments are better done with the eyes closed because response variation is less than with the eyes open in darkness. I don't know why.

